BAMS
Meeting Summary

# PARMIO

## A Reference Quality Model for Ocean Surface Emissivity and Backscatter from the Microwave to the Infrared

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**ISSI Science Team Meeting Report on Development of a Reference Quality Model for Ocean Surface Emissivity and Backscatter from the Microwave to the Infrared**

***What***: An international team of scientists, with backgrounds in radiative transfer modeling, data assimilation, field campaigns, space agencies, and instrumentation, developed a reference quality model for ocean surface emission and backscatter.

***When***: 18–19 October 2022

***Where***: International Space Science Institute, Bern, Switzerland

**KEYWORDS:** Sea/ocean surface; Satellite observations; Radiative transfer; Microwave observations; Infrared radiation; Scatterometer

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The need for a community reference quality ocean emission and reflection model for use across a broad spectral range [microwave (MW) and infrared (IR)], as well as supporting passive and active remote sensing, has been identified in various reports and international workshops. Notably, the European Commission Horizon2020 project, GAIA-CLIM (www.gaia-clim.eu), identified in Deliverable D6.11 that the lack of a reference-quality ocean emission and backscatter model was a major gap in our ability to provide absolute calibration of the satellite-based observing system. The gap was also identified by the ECMWF–JCSDA–NWPSAF all-sky assimilation workshop in December 2015 and again in February 2020 and the twenty-first meeting of the International TOVS Working Group in December 2017.

On 18 and 19 October 2022, an international science team of the International Space Science Institute (ISSI) met for the final meeting of a project started in November 2019 to develop a reference model, with the objective of it being maintained and supported, with traceable uncertainty estimation, with documented and freely available code, allowing for new science for MW to IR, and with capability to support passive and active applications (including with bidirectional reflectance distribution function, BRDF).

The meeting was split into four main parts. First, the reference model was presented with discussion of the parameterization options for its various components. Second, evaluation and validation of the model was reported in the microwave and in the infrared, for passive and active applications. Third, a fast model based on the reference model for use in data assimilation was presented. Finally, the next steps for the model development and dissemination were discussed. The reports and findings of the ISSI team are available at www.issibern.ch/teams/oceansurfemiss/, where presentations are also available. This is a short meeting report to bring the team's activities to the attention of a wider audience.

## Reference model for ocean surface emissivity and backscatter from the microwave to the infrared

The Passive and Active Reference Microwave to Infrared Ocean (PARMIO) model is a modular computer model coded in FORTRAN that computes the ocean surface emissivity and reflective properties from the microwave (~0.5 GHz) to the infrared (~400 nm). The code base was initially developed for applications at 1.4 GHz at the Laboratoire d'Océanographie et du Climat: Expérimentations et Approche Numérique (LOCEAN) (Dinnat et al. 2003), adapted from the theory developed for applications at higher microwave frequency (19 and 36 GHz)

(Yueh 1997). The team worked on updating the model parameterizations to improve its physical consistency over a large frequency range, for active and passive applications, and on validating the model using multi sensor observations (e.g., Kilic et al. 2019) and geophysical model functions (GMF).

The model parts the ocean surface into contributions from foam-covered and foam-free surfaces. The foam-free surface is modeled with a two-scale model where the surface roughness scales are split in two domains according to their size compared to the sensor electromagnetic wavelength. The small-scale roughness is defined as ocean waves with a height much smaller than the electromagnetic wavelength and their impact is accounted using the Small Perturbation Method (SPM) asymptotic electromagnetic model. The large scales are waves with horizontal length larger than the electromagnetic wavelength and their impact is modeled according to the geometric optics (GO) theory. The two-scale approach treats waves as a superimposition of the small scales riding on top of the large waves. The separation of the two scales is parameterized through a cutoff wavenumber that is adjustable (usually set to the wavenumber corresponding to a wavelength between 3 and 5 times the electromagnetic wavelength). The foam-covered surface accounts for large waves only using geometric optics. The model allows the user to run the code for the GO, the SPM, or the two-scale model configurations.

The statistical description of the various roughness scales of the sea surface is through a sea spectrum model. The models available are Durden and Vesecky (1985), which was developed at L-band (1.4 GHz) and has been made adjustable in amplitude in PARMIO to use it as designed by Yueh (1997) and Yin et al. (2016), who adjusted the model using radiometric observations, and Elfouhaily et al. (1997), which was developed independently of remote sensing data, showed good performances for C-band (~5 GHz) scatterometers, and includes a wave development parameterization with the inverse wave age is an input parameter. Because of unexpected behavior of the Elfouhaily et al. model at L-band in the wind speed range 3–7 m $s^{-1}$, the team has used a tuned version of the Durden and Vesecky model as default configuration for the reference model. It should be noted that some choices of sea spectrum require a consistent foam model as both models were tuned together. The spectrum model is used directly in the computation of the SPM component and impacts the GO component through the slope variance of the large-scale waves. Another option in PARMIO is to compute the slope variance used in the GO using the frequently used wind-dependent empirical relationship by Cox and Munk (1954).

The seawater reflective and emissive properties are derived from a flat surface component to which the impact of roughness is added according to the models described in the previous paragraph. Both the flat and rough surface contributions use a dielectric constant model for seawater to derive the dependence of the dielectric properties to water temperature, salinity, and the electromagnetic frequency of the sensor. Models implemented in the code are Klein and Swift (1977), which was developed from laboratory measurements at 1.4 and 2.65 GHz and is routinely used at 1.4 and ~7 GHz, although biases in cold waters have been reported (Dinnat et al. 2019; Shibata 2013); Ellison et al. (1998), developed from laboratory measurements between 3 and 20 GHz and at spot frequencies 23.8, 36.5, and 89 GHz; Meissner and Wentz (2004, 2012), an empirical parameterization adjusted and validated using remote sensing observations from 1.4 to 89 GHz; a high-frequency model developed for the project at frequencies from 28.8 GHz and up to 449,677 GHz (~670 nm) in the infrared that uses the pure water model of Rowe et al. (2020) with a correction derived from Pinkley and Williams (1976) to account for salinity. The team selected the Meissner and Wentz parameterization as the default configuration for the reference model in the microwaves.

The properties of the foam-covered surfaces are modeled using a foam dielectric model and a foam coverage fraction model for the foam layer. As mentioned previously, the roughness modeling for foam-covered surface comes from the underlying large waves, which tilt the foam-covered surface, changing the local geometry (e.g., incidence angle, polarizations). The foam coverage fraction is usually a power law of the wind speed, and sometimes a function of temperature of the water and air above the sea surface. Several models for foam coverage are implemented: Monahan and O'Muircheartaigh (1986) has been used in both active and passive remote sensing and is a function of wind speed and atmospheric stability; Monahan and Lu (1990) distinguishes between different lifetime stages for foam bubbles; and Yin et al. (2016) is a semiempirical model, is adjusted on radiometric observations at L-band, and has different parameterizations according to sea spectrum and ancillary wind product used. The implemented models for foam emissivity involve different degrees of complexity. The model by Stogryn (2005) is a simple empirical parameterization of foam emissivity as a function of polarization, incidence angle, and frequency developed between 13.4 and 37 GHz. More recent models by Anguelova and Gaiser (2013) and later Yin et al. (2016) use a physical parameterization that accounts for foam as a multilayered medium with varying vertical air fraction. The Yin et al. (2016) model adjusted its parameters to fit radiometric observations at 1.4 GHz. Due to varying accuracy of the emission model when compared to observations at various frequencies, the team developed tuned foam parameterizations that are used as reference configurations for PARMIO. One parameterization adjusted a unique set of values for the wind coefficients in the coverage fraction model, the effective foam thickness, and the void fraction at the air–water interface (Kilic et al. 2023, manuscript submitted to *Earth Space Sci.*). It has been used to develop the Surface Fast Emissivity Model for Ocean (SURFEM-Ocean) discussed below. A second foam parameterization uses another approach to optimize the model at multiple frequencies by adjusting the foam effective thickness and void fraction at the air–water interface as functions of frequency and polarization to fit radiometric data between 1.4 and 89 GHz (Anguelova et al. 2022).

Following the team discussions at the final meeting, a component for multiple reflections was implemented to account for the reflection of the emission from the sea surface, which becomes important at large incidence angles. The surface-emitted surface-reflected (SESR) model by Masuda (2006) was modified to account for polarization and implemented in PARMIO. Another addition to the model following the meeting's discussions is the possibility to output a polarized BRDF, which is needed to compute the contribution of reflected downwelling atmospheric emission.

The reference configurations defined by the team are documented by two configuration files and validation output files (for the users to check the consistency of their calculations) provided with the code.

## Validation and evaluation of the reference model

Systematic comparisons have been conducted between PARMIO simulations and satellite observations (e.g., Kilic et al. 2023, manuscript submitted to *Earth Space Sci.*) from the Soil Moisture Active Passive (SMAP) radiometer (Entekhabi et al. 2010) at 1.4 GHz, the Advanced Microwave Scanning Radiometer 2 (AMSR2) (Maeda et al. 2016) from 6.9 to 89 GHz, the GPM Microwave Imager (GMI) (Hou et al. 2014) from 10.6 to 166 GHz, and the Advanced Technology Microwave Sounder (ATMS) (Kim et al. 2014) between 23.8 and 165.5 GHz. Parameters of PARMIO were adjusted to mitigate differences with satellite observations across frequencies, particularly in cold water and at high winds for frequencies above 6 GHz where the differences were the largest. Additional validation of PARMIO using observation from WindSat was proposed, by leveraging a WindSat brightness temperature (TB) dataset produced in the framework of the preparation of the Copernicus Imaging Microwave Radiometer (CIMR) mission. The product offers absolute calibrated TB, and WindSat is a good proxy to CIMR, covering frequencies from 6 to 37 GHz, and full polarimetry at 10.7, 18.7, and 37.0 GHz.

PARMIO was also compared to the Advanced Radiative Transfer Modeling System (AMRS), an ocean two-scale model that has been developed in China and that provides polarized BRDF, suitable for vector radiative transfer model. The surface Stokes emissivity vector and monostatic and bistatic normalized radar cross-section can be calculated from the BRDFs. Surface emissivity and backscattering results are compared with PARMIO, showing good agreement between the models.

PARMIO was also compared to observations from active microwave instruments. Comparisons between backscattering GMFs and PARMIO simulations, at L, C, and Ku bands, using different wave spectrum model, showed significant discrepancies between the simulations and the GMFs, and no consistent explanation is provided so far. Wind accuracy was discussed, with recent improvements in wind retrievals with scatterometers being presented, emphasizing the accuracy of the GMF and the stability of the ASCAT instruments (Gelsthorpe et al. 2000). Compared to the high-quality estimation of the wind vectors with scatterometers, winds from the European Centre for Medium-Range Weather Forecasts appear to be biased, and a correction scheme is being developed.

PARMIO was modified to be extended to the infrared. As mentioned previously, an infrared dielectric model has been implemented and tested in PARMIO. The two-scale model simulations converge to the geometric optics limit at high frequency, as expected. Preliminary results with the foam model seem to indicate higher values than literature results. Comparisons with the current Radiative Transfer for TOVS (RTTOV) IR emissivity model (IREMIS) show close agreement with PARMIO when neglecting the multiple reflection terms in IREMIS. Following this discussion, a multiple reflection component was added to PARMIO (see previous section) and is being evaluated.

## A fast emissivity model

PARMIO was used as the reference for the development of a fast passive microwave emissivity code. SURFEM-Ocean uses an artificial neural network (NN) to reproduce the results obtained with PARMIO much faster (Kilic et al. 2023, manuscript submitted to *Earth Space Sci.*). It extends the frequency coverage of the previous fast ocean surface emissivity model for microwave frequencies FASTEM (English and Hewison 1998; Liu et al. 2011) to 0.5–700 GHz and includes the computation of the Jacobian, the tangent linear model, and its adjoint for an efficient use in numerical weather prediction (NWP) applications. SURFEM-Ocean has been compared to multiple satellite data and other models with satisfactory results. It improves precisions at low microwave frequencies, at high incidence angles, and for cold temperatures and high wind speeds. It has been incorporated in RTTOV (https://nwp-saf.eumetsat.int/site/software/rttov/), the fast radiative transfer model for passive visible, infrared, and microwave downward-viewing satellite radiometers, spectrometers, and interferometers. Initial tests were presented at the meeting, with comparisons to FASTEM. SURFEM-Ocean is now distributed in the latest version of RTTOV (13.2), released in December 2022. It is already being evaluated, with encouraging results, for operational use at leading NWP centers; for example, it is targeting ECMWF’s Cycle 49r1 operational system.

## Next steps

Significant progress has been done by the team for passive microwaves and infrared applications. However, simulations of the active microwave responses with PARMIO do not reproduce well the observations. More efforts will have to be dedicated to the improvement of the simulation of active observations, in close relationship with the active microwave community. Recent developments suggest that improvement is possible through a better description of the surface waves (Plant and Irisov 2017). Having a unified forward model for both passive and active microwaves would enable a consistent use of both types of observations. Possible improvements in the foam emissivity modeling in the microwave have also been mentioned, for example, by accounting for scattering in the foam layer above 90 GHz. In the infrared, the foam emissivity must be tuned and changing the void fraction might help getting closer to the laboratory measurements. Additional validation of the microwave emissivity modeling sensitivity to the wind direction, especially for high wind speeds, was also recommended. This could be done with the WindSat dataset presented at the meeting. Research is still ongoing in the community to further improve the accuracy of microwave emissivity models, and the aim is for PARMIO to provide a comfortable environment for integrating various model components (e.g., wave spectra, dielectric constant models) within a unified electromagnetic transfer modeling framework.

Differences between PARMIO and other models in the infrared were attributed to the fact that multiple reflections were not taken into account in PARMIO. The latest version of PARMIO now includes a multiple reflection component and new evaluations in the infrared are being conducted. Following the SURFEM-Ocean initiative for the passive microwaves, there is interest in developing a fast emissivity model in the infrared. Once the PARMIO multiple reflections model has been validated, a fast model could be computed and implemented in RTTOV to replace IREMIS. That would provide improved consistency from microwave to infrared ocean emissivity for assimilation.

The model code will soon be released publicly for use and further development by the community.

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